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Title:	Physics Beyond the Standard Model through Neutron Beta Decay
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Physics Beyond the Standard Model through Neutron Beta Decay

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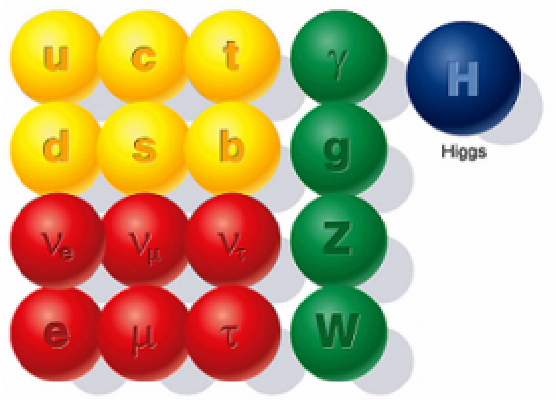
August 28, 2013

The Standard Model (and Beyond)



Some curiosities

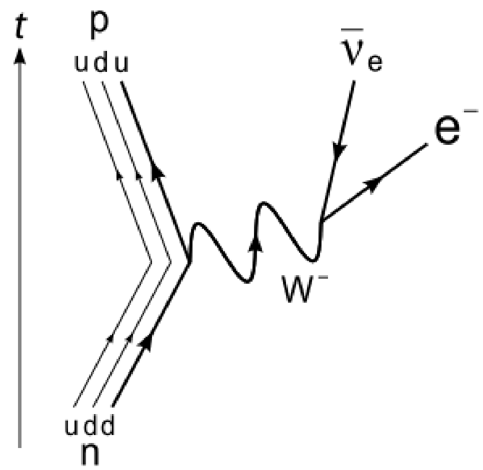
- Lots of "Why?" questions
  - Why 3 generations?
  - Why so many parameters?
  - Why these masses?
  - Why left-handed weak interaction?
- What is Dark Matter?
- Why so much matter?
- Where is gravity?
- And more...

Finding the missing pieces

- High Energy frontier (LHC) vs. Precision frontier (beta decay)
- High energy: Direct search for heavy particles
- Precision: Measure deviations from SM
- Complementary limits

Neutron Decay

- Semileptonic charged weak interaction
- Standard Model: V - A form
- $\tau_n \approx 15$ minutes



Decay Distribution

- Observables: effective correlations coefficients

$$\frac{d\Gamma}{dE_e d\Omega_e d\Omega_\nu} \propto w(E_e)(1 + \frac{m_e}{E_e}\overline{b} + \overline{a}(E_e)\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + \overline{A}(E_e)\frac{\vec{\sigma}_n \cdot \vec{p}_e}{E_e} + \overline{B}(E_e)\frac{\vec{\sigma}_n \cdot \vec{p}_\nu}{E_\nu} + \cdots)$$

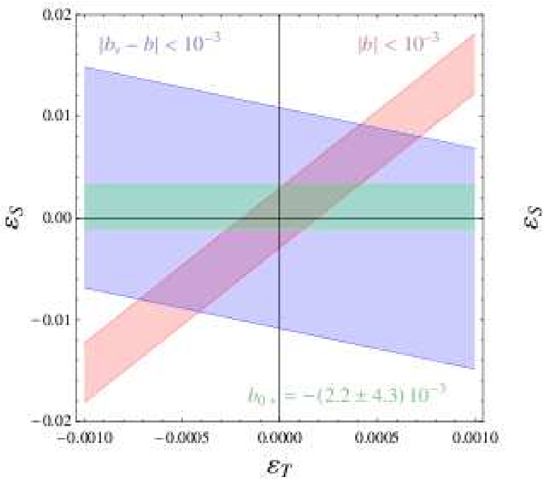
Testing the Standard Model

- **A**, **a** $+ \tau_n \rightarrow$ V, A interactions (V_{ud}, RL symmetry, ...)
- **B**, **b** $\rightarrow$ S, T interactions (BSM interactions, MSSM, ...)

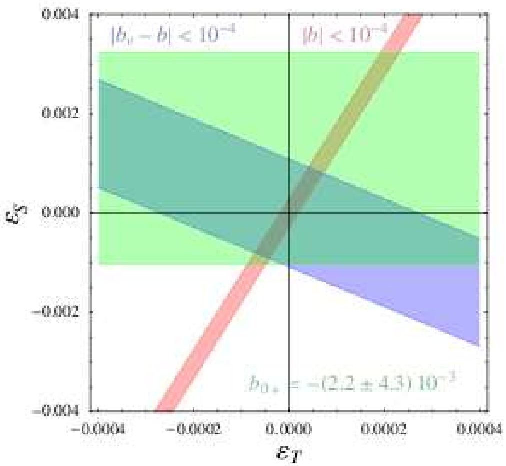
Motivation[1]

- S, T interactions appear at linear order in B, b
- Presence of S, T interactions at 10^{-3} indicate BSM physics

10^{-3} level precision



10^{-4} level precision



- Assume no uncertainty on $g_{S,T}$
- Green band from superallowed $0^+ \to 0^+$ decays, red band from b, blue band from B

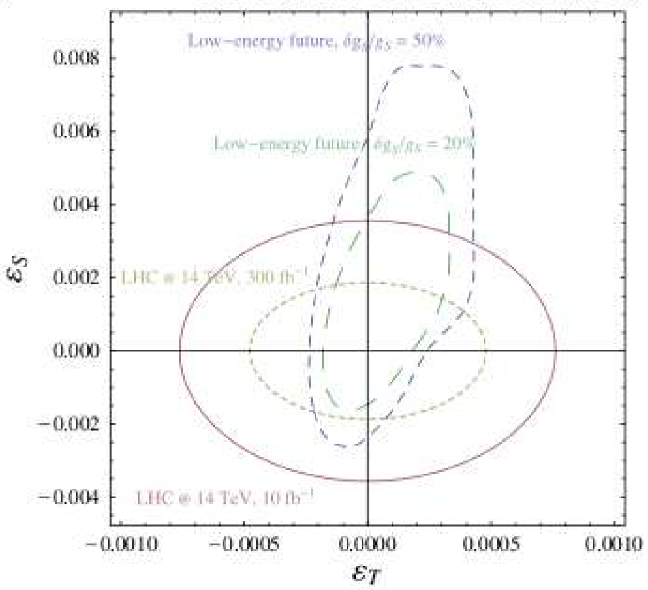
[1] Phys.Rev.D **85**, 054512 (2012)

Motivation

System Comparison: Extracting ϵ_S,ϵ_T

- Current limits from $0^+ \to 0^+$ decays, LHC not yet competitive
- LHC upgrade: complementary to 10^{-3} level B, b measurements
- 10^{-4} level measurements: unmatched discovery potential!

PHYSICAL REVIEW D 85, 054512 (2012)



Status of B

- $B = 0.9807 \pm 0.0030 (0.3\%)$ (PDG 2008)
- polarized cold neutron experiments
- GOAL: $\sim 0.1\%$ measurement, establish feasibility of 0.01% measurement

Ultracold Neutrons

Class	Energy	Source
Fast	> 1 MeV	Fission reactions / Spallation
Slow	eV – keV	Moderation
Thermal	0.025 ev	Thermal equilibrium
Cold	μeV – meV	Cold moderation
Ultracold	≤ 300 neV	Downscattering

How cold is Ultracold?

- Temperature < 4 mK
- Velocity < 8 m/s
- Usain Bolt ~ 12 m/s

UCN can be bottled

- Gravitational ($V = mgh$): 100 neV / meter
- Magnetic ($V = -\vec{\mu} \cdot \vec{B}$): 60 neV / Tesla
- Material $\left(V = \frac{2\pi\hbar^2 Nb}{m} \right) \begin{cases} ^{58}\text{Ni} : & 335 \text{ neV} \\ \text{DLC} : & 250 \text{ neV} \\ \text{BeO} : & 250 \text{ neV} \\ \text{Cu} : & 170 \text{ neV} \end{cases}$

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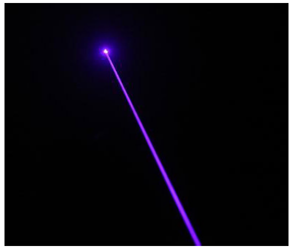
Ultracold Neutrons vs. Cold Neutrons

Features of CN experiments

- "Beam" of neutrons
- High polarization using supermirror
- Higher neutron generated background
- Ambient (reactor) background
- High decay rates

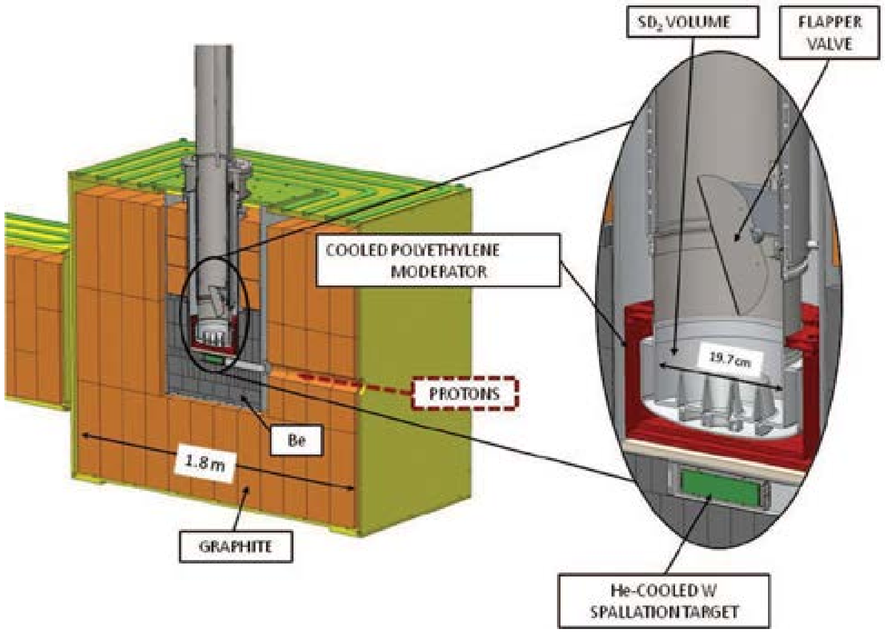


Features of UCN experiments

- Defined decay volume
- 100% polarized using magnetic fields; limited depolarization due to material surfaces
- Small neutron-generated backgrounds
- Pulsed beam: limits backgrounds
- Limited statistics

The LANSCE UCN Source[1]

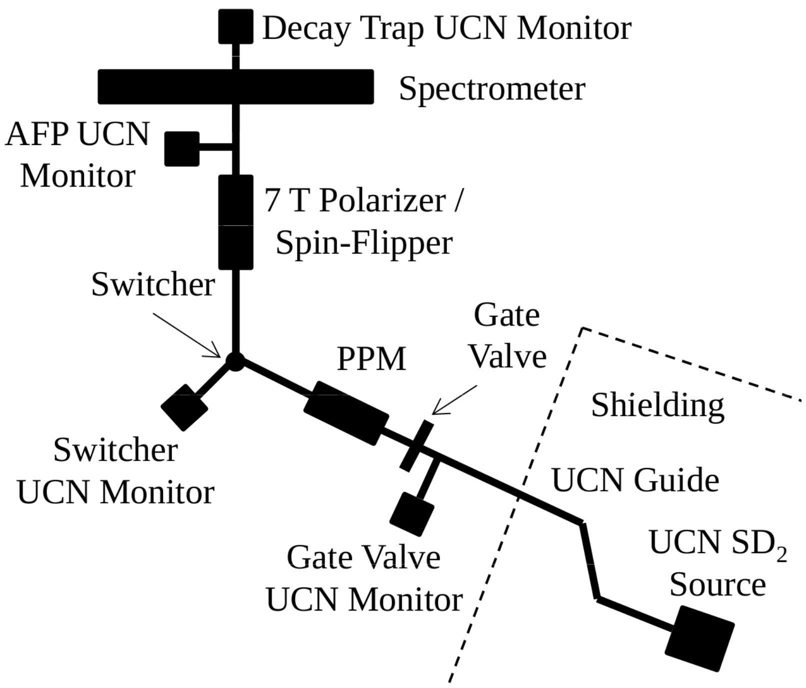
- 800 MeV proton beam + tungsten target → spallation neutrons
- Single scatter in solid deuterium: CN→UCN + phonon
- Remove phonons: SD_2 cooled to 4K
- "Flapper" valve shields UCN from SD_2
- High density at shield wall: 50 UCN/cc
- Pulsed beam: Low background



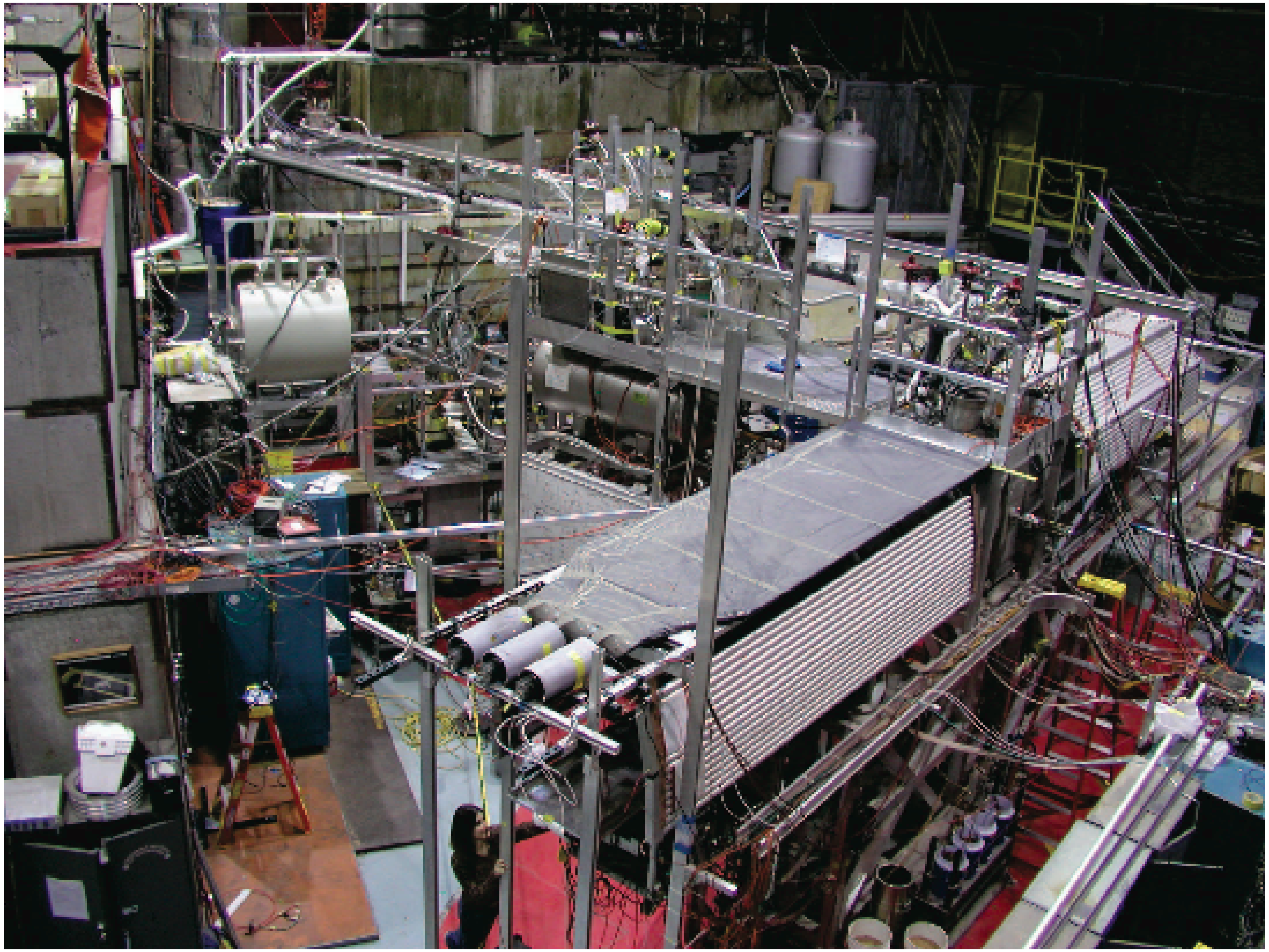
[1] Rev. Sci. Instrum. 84, 013304 (2013)

Experimental Area B

- DLC-coated quartz and copper UCN guides
- 7 T Polarizer: $> 99.5\%$ UCN polarization
- AFP spin flipper
- 1 T electron spectrometer



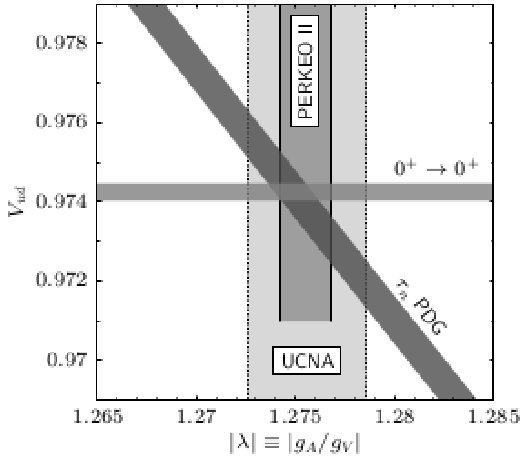
Experimental Area B



UCN Experiments at Area B

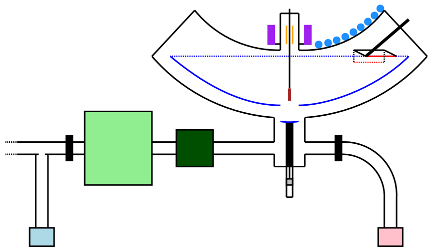
UCNA: neutron β-asymmetry[2]

- "Flagship" experiment
- First measurement of **A** using UCN
- Latest result $A_0 = -0.11954(112)$, used to determine $\lambda = g_A/g_V = -1.2756(30)$
- $\lambda + \tau$ can extract V_{ud}, test CKM unitarity



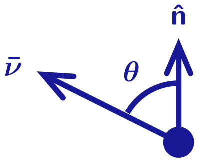
UCNτ: neutron decay lifetime

- Recent measurements inconsistent
- New experiment: magneto-gravitational trap
- Successful test of prototype trap: $\sim$10 hr storage time



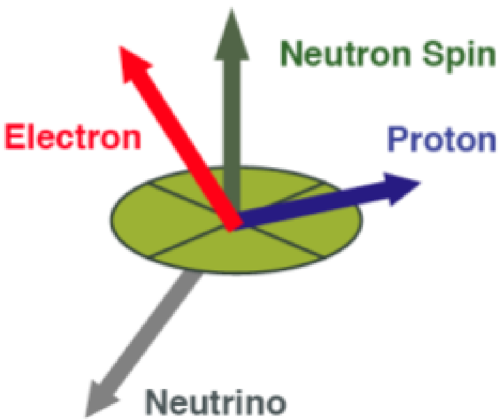
[2] Phys. Rev. C 87, 032501(R) (2013)

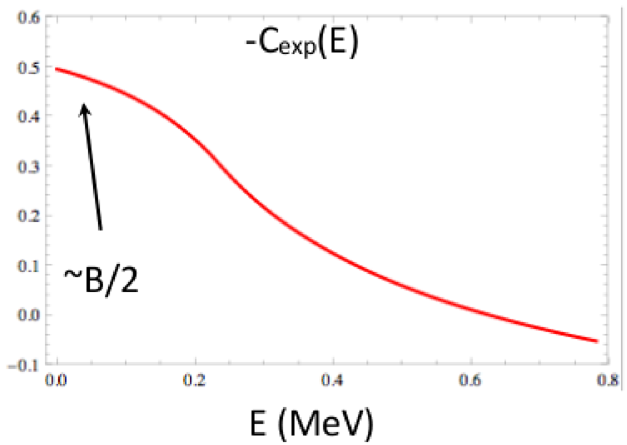
UCNB: Antineutrino Asymmetry B



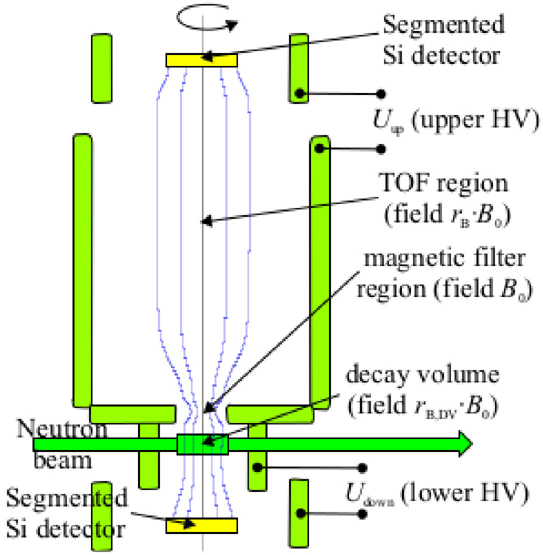
Extracting B

- 3-body decay: Detect proton & beta in coincidence
- Count $N^{\beta p} = N^{\pm\pm}$ = aligned vs. antialigned with σ_n
- $B_{exp}(E) = \frac{N^{--}(E) - N^{++}(E)}{N^{--}(E) + N^{++}(E)}$
- $C_{exp}(E) = \frac{(N^{++}(E) - N^{-+}(E)) - (N^{+-}(E) - N^{--}(E))}{(N^{++}(E) - N^{-+}(E)) + (N^{+-}(E) - N^{--}(E))}$
- Statistical sensitivity $\frac{\delta B}{B} = \frac{2.9}{\sqrt{N}}$: 1 month to reach 10^{-3} level at 10Hz decay rate





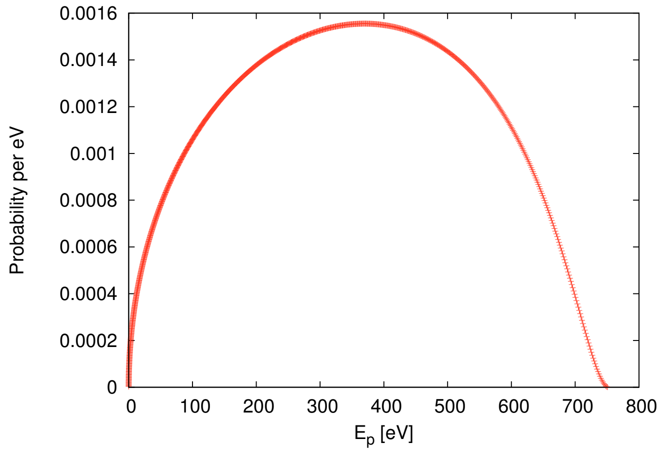
Partnership with Nab



- Experiment planned for Spallation Neutron Source at Oak Ridge National Laboratory
- Will measure **a**, the electron-neutrino correlation, and **b**, the Fierz interference term
- No polarized neutron requirement
- **a** has similar sensitivity to λ as **A**
- **b** should be zero in the Standard Model
- Similar experimental/detector requirements as UCNB

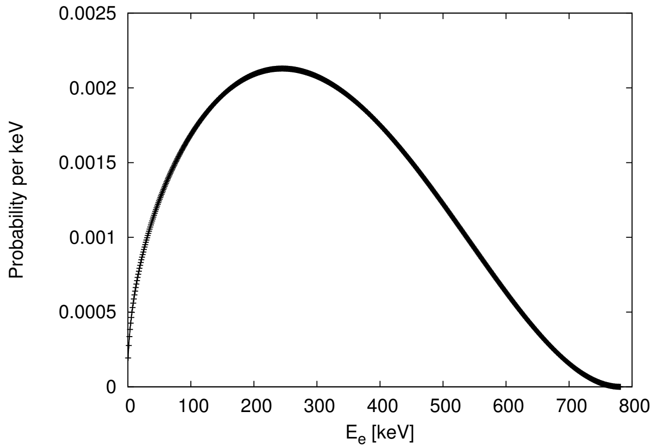
CHALLENGE: Detecting protons and betas

Proton Energy Spectrum



- max E $<$ 800 eV
- slow timing: 10 μs to 1 ms after decay
- Very low energy: detector deadlayer important

Electron Energy Spectrum



- max E $\approx$ 800 keV
- fast timing: 10 ns
- problem: backscattering $\rightarrow$ partial energy signal

System Requirements

Detect Protons

- Bias detector to ~30 kV: accelerate protons
- Thin deadlayer to minimize energy loss
- Very low noise required: cool to LN_2 temperatures

Detect Electrons

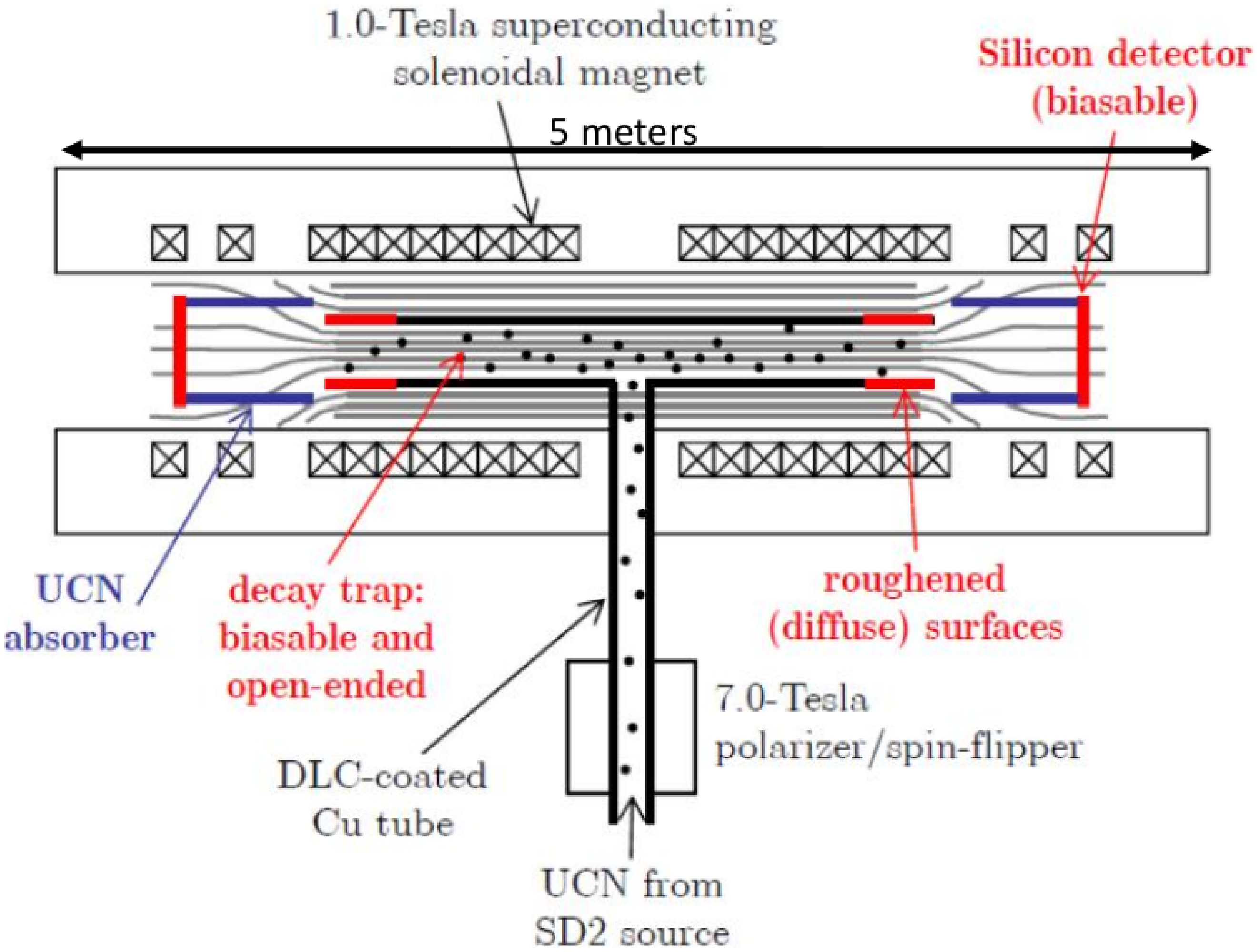
- Backscattering probability on silicon very high
- Fast timing to resolve backscattered events

Detect Coincidences

- 1 T Magnetic field operation: guide charge particles to detectors
- Proton, electron maximum Larmor radius $\approx$ 4 mm
- Check coincidence in adjacent pixels

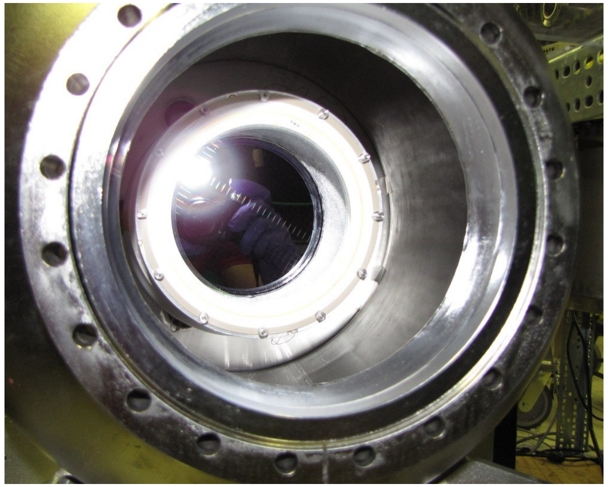
Experimental Approach

- UCN bottled in decay trap
- Protons/Electrons guided by 1 T field to Detectors
- Detectors biased -30kV to accelerate protons
- Entire DAQ biased with detectors

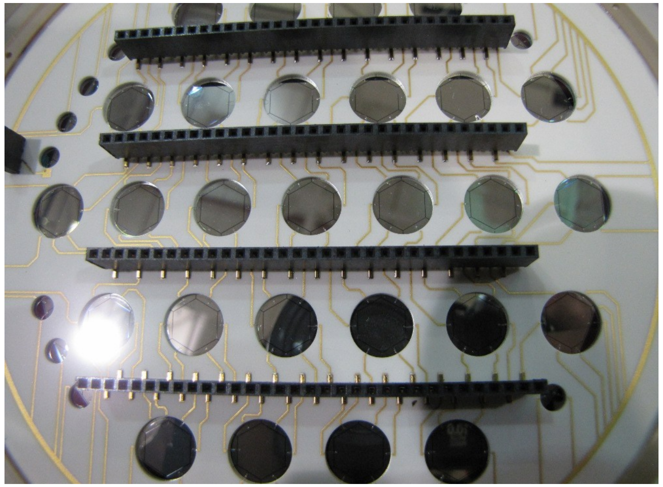


Large area silicon detectors

Junction Side (charged particle entry)



Ohmic Side (Electronics)

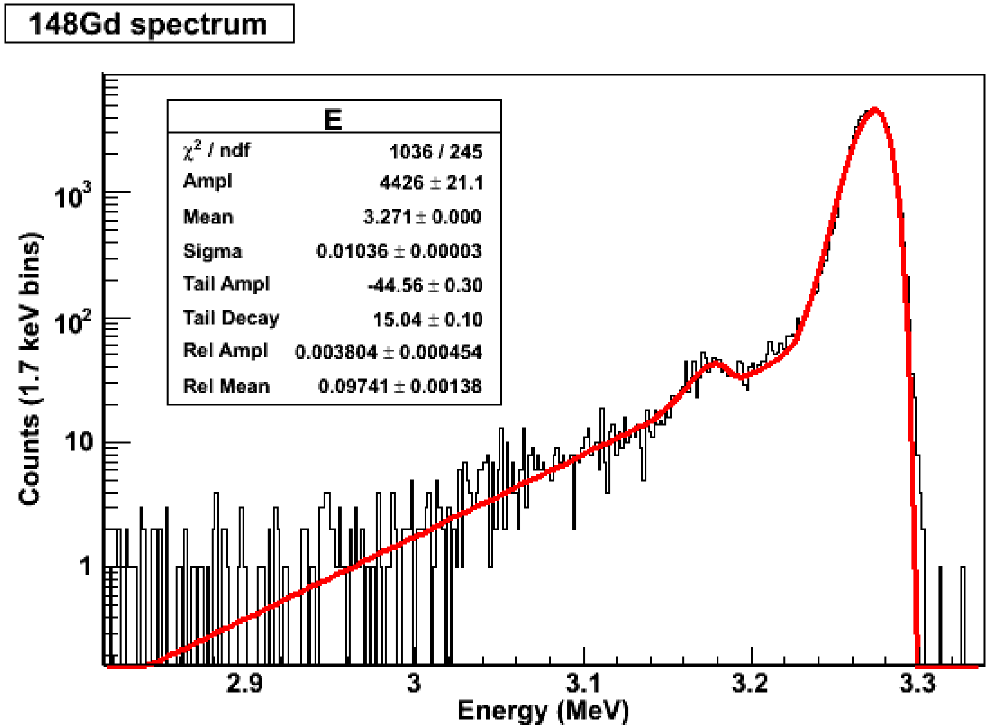


- 12 cm diameter active area, 2 mm thick
- Hexagonal array of 128 pixels, each 0.8 cm^2 area
- p-type implant minimizes "deadlayer"
- Metallized Al mesh $\rightarrow$ improve charge collecting time
- Detect both protons and betas

Single pixel characterization - Using α particles

^{148}Gd source

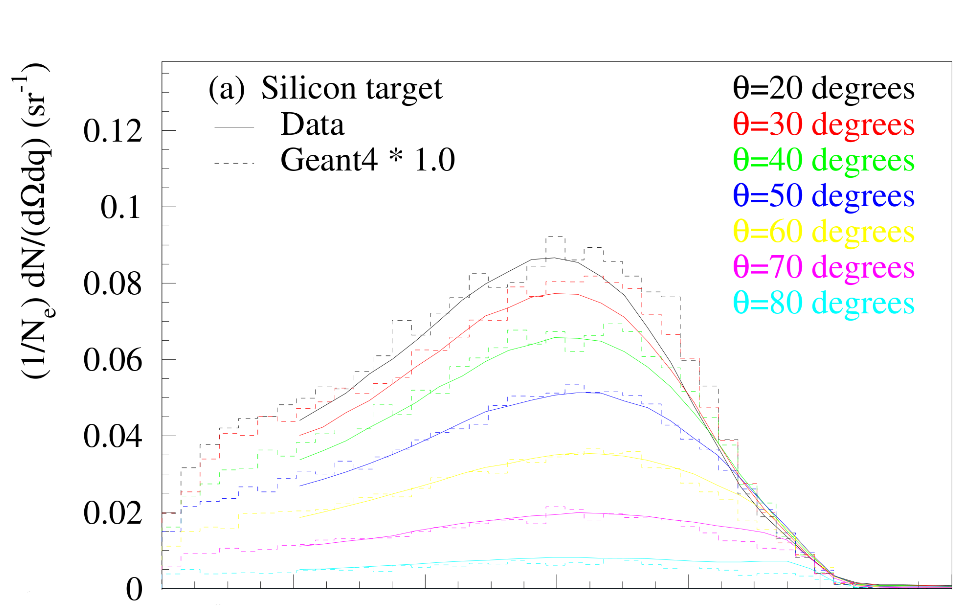
- Single alpha peak at 3.271 MeV
- Warm detector + simple DAQ: 10 keV resolution
- Effect of Al mesh observed
- Extract deadlayer=100$\pm$20 nm



Electron Backscattering

- High backscatter probability: small mass m_e, high Z of silicon
- $(\frac{d\sigma}{d\Omega})_R \propto (\frac{Ze^2}{2\mu v^2 sin^2(\frac{\theta}{2})})^2$
- Minimize effect: detectors mounted in low field region
- Fast data acquisition allows time resolution and correction of backscatter events

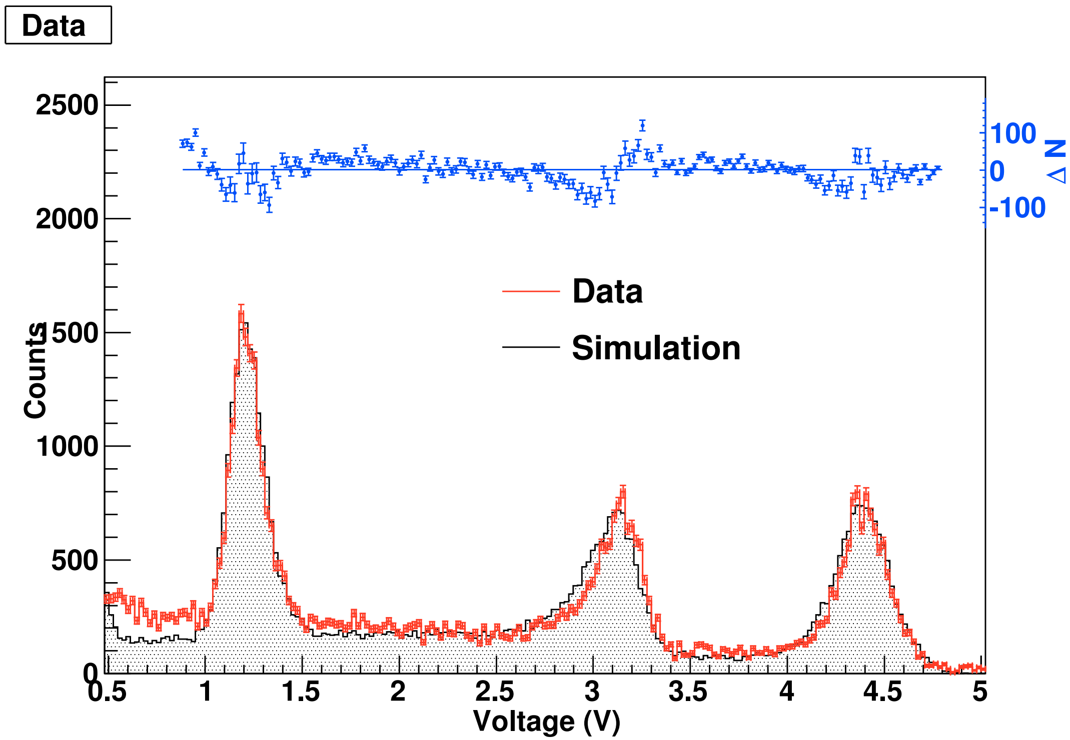
Martin et al 2003



Detector characterization

^{109}Cd source

- Expect X-rays at $\sim$ 23 keV, Auger electrons at 63 keV and 84 keV
- detector geometry simulated using PENELOPE

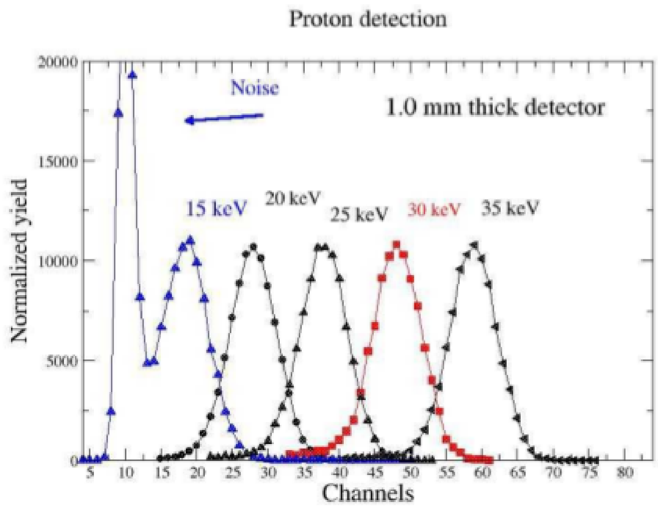


Proton detection

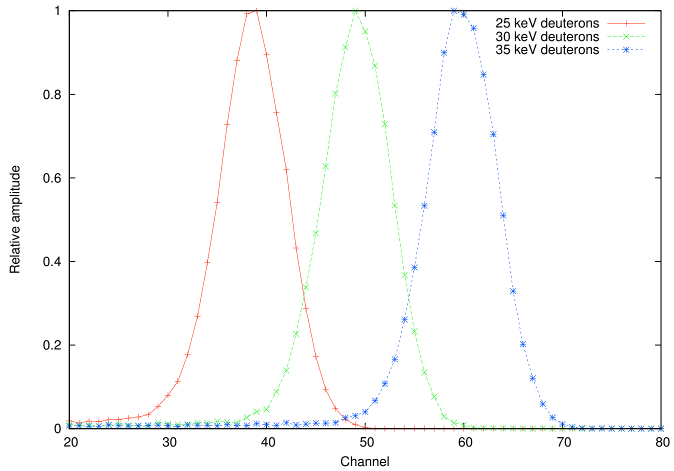
TUNL mini proton beam

- TUNL accelerator: proton energies from 10 keV to 60 keV
- 1 mm Si detector cooled to $\sim$ -15°C
- <20 keV protons resolvable
- $\sim$1.5 keV silicon equivalent energy resolution
- Deadlayer measured using protons: 100.4 $\pm$ 2.3 nm
- Deadlayer measured using deuterons: 93.7 $\pm$ 16.0 nm

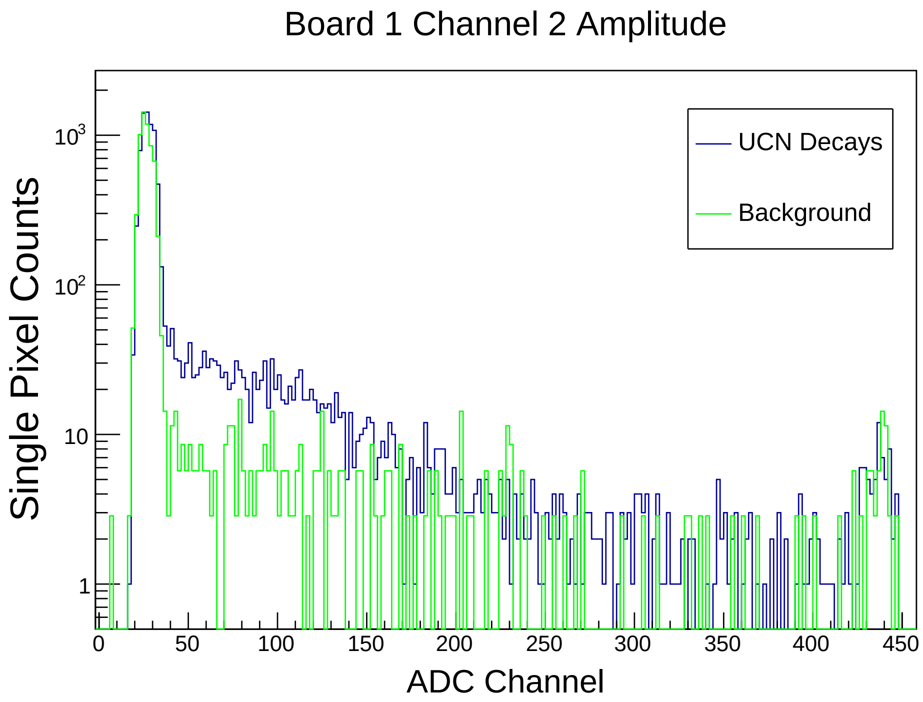
Protons



Deuterons

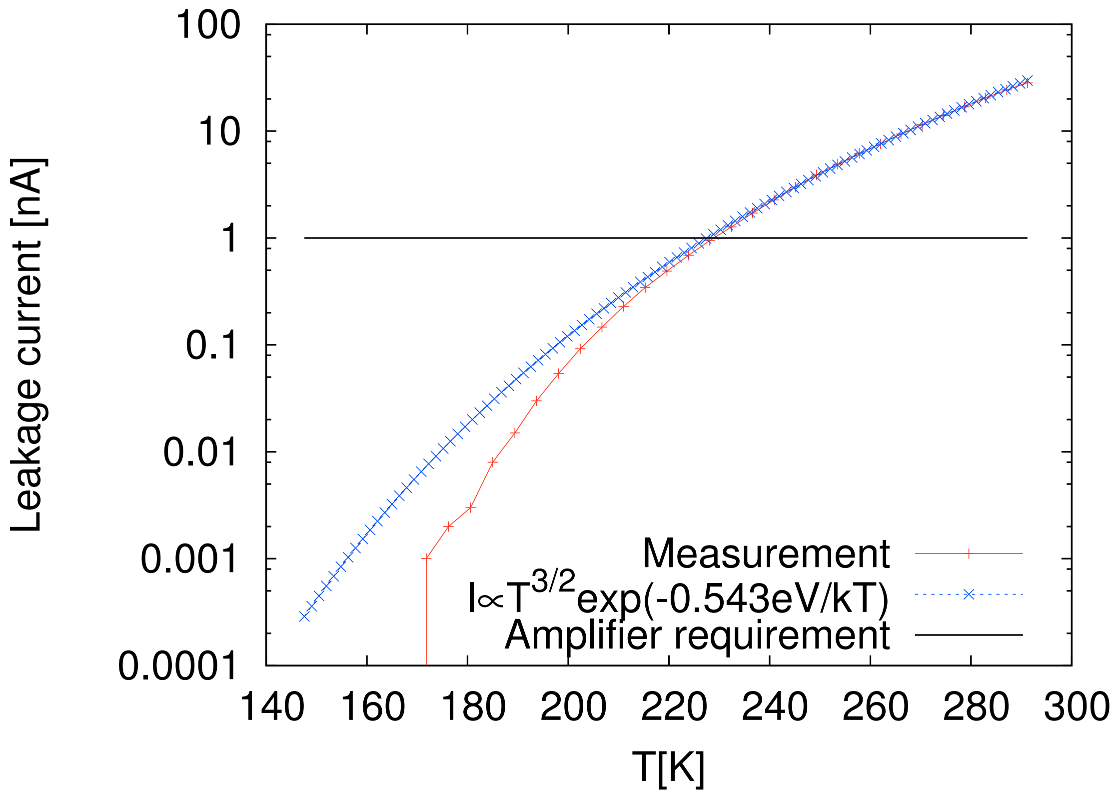


UCN beta decay measurement (ongoing)



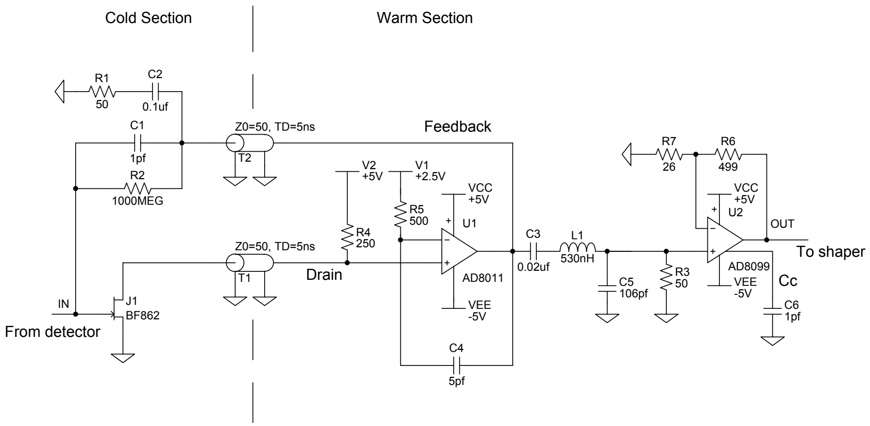
- Beta spectrum from neutron decay
- 1 mm "Test" (higher noise) detector
- 5 hours of beta-decay, 2 hours background
- Current rates $\sim$0.1 Hz/pixel

Leakage current

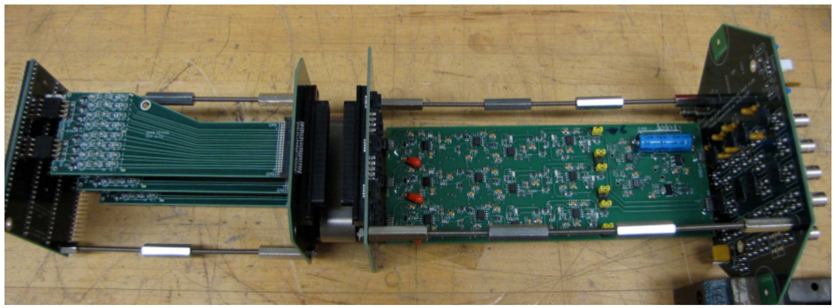


- Leakage current is function of detector temperature
- Effectively zero at T $<$ 180 K
- Amplifier can operate ideally with FET at T $<$ 220 K

Amplifier design

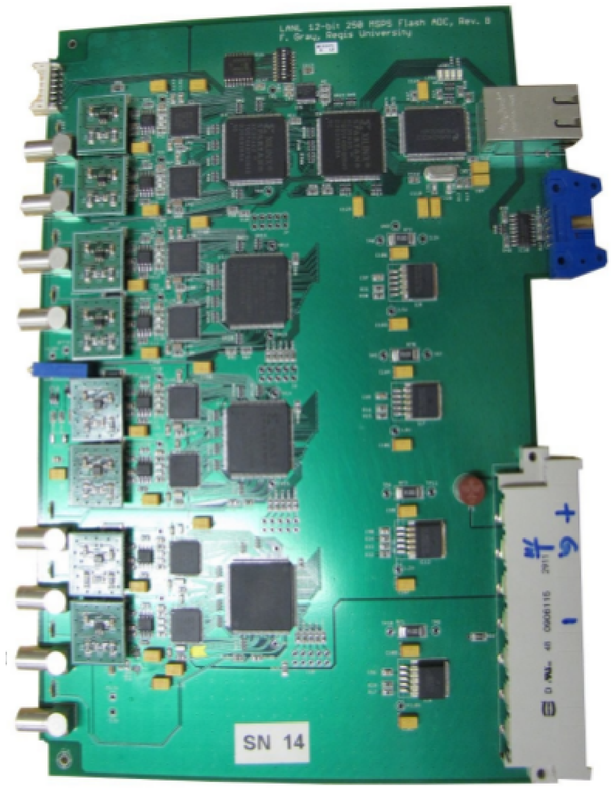


- Custom design (Pat McGaughey and Jacqueline Mirabal)
- FET mounted at detector, separated from rest of amplifier $\rightarrow$ avoid pickup noise
- Cool detector + FET assembly to LN_2 temperatures: FET at $\sim$100 K $\rightarrow$ avoid thermal noise
- Minimum rise time $\sim$ 5 ns
- Theoretical noise $\sim$ 1.3 keV
- Up to 24 ch per detector

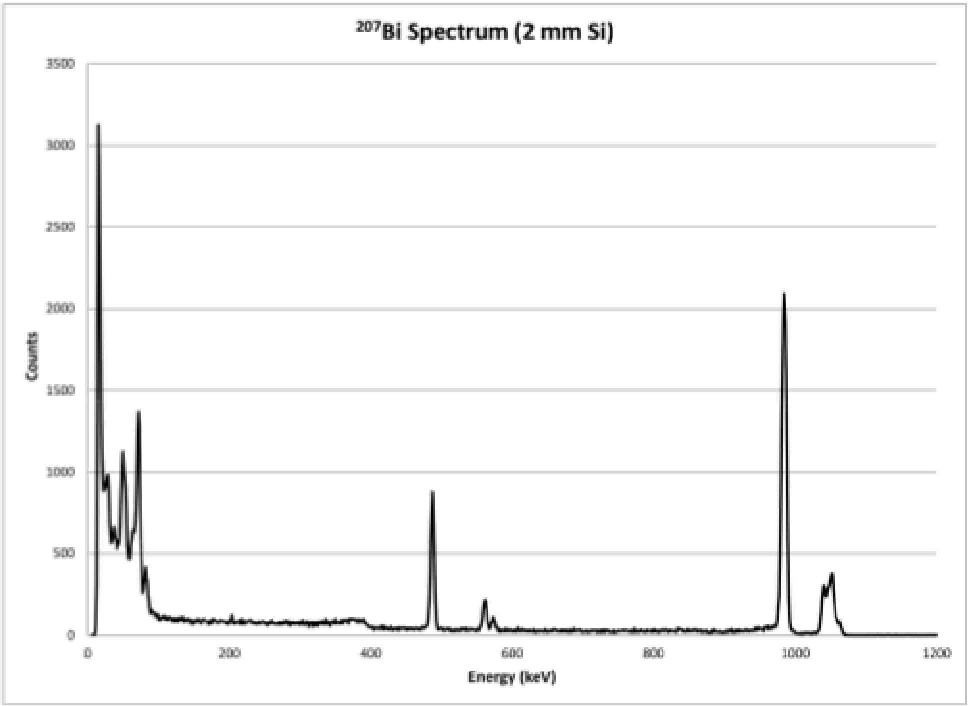


Waveform Digitizers

- 250 MHz: take advantage of fast timing
- Custom 8 channel, 12 bit FADCs
- Testing filter algorithms for improved resolution, noise discrimination
- MIDAS DAQ software package used to acquire events

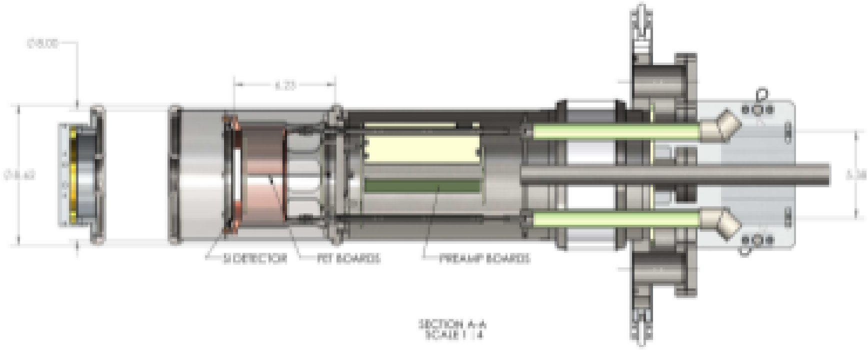


Noise Characterization

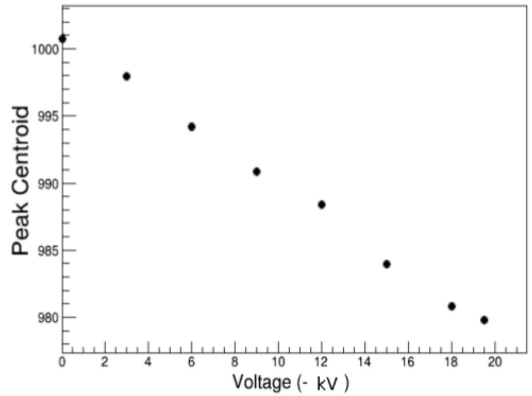


- 2 mm detector, 100 K temperature
- ^{207}Bi β source
- On the test bench: energy resolution $\sim$ 2 keV $= 2\times$ theoretical noise
- In the lab: energy resolution $\sim$ 2.5 keV

Improved Biased Detector Apparatus



- Full DAQ biased: detector, amps, digitizers
- Fiber from DAQ to computers
- Apparatus tested to -36 kV with detector surrogate
- Data taken at up to -20 kV, 1 T field, with working detector
- New bias cage for DAQ now being installed



^{207}Bi source (976 keV peak)

Current Status

Summary

- System capable of detecting < 20 keV protons
- Beam is on! Now detecting betas from neutron decay
- Some tuning to eliminate accelerator noise required
  - Gains from improved shielding, isolation, passive filtering, digitized event processing

Coming soon

- Instrument full 24 channels
- First detection of protons from neutron β-decay
- First detection of proton-electron coincidences
- Study timing, energy, angle-effects using dedicated sources
- Preliminary goal: 0.1% statistical uncertainty
- Evaluate requirements for 0.01% uncertainty measurement

Collaboration List

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